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Performance Assessment of the Three-Dimensional Wind Field Weather Running Estimate–Nowcast and the Three-Dimensional Wind Field Air Force Weather Agency Weather Research and Forecasting Wind Forecasts

by Robert E. Dumais, John W. Raby, Yansen Wang, Yasmina R. Raby, David Knapp

ARL-TN-0514 **December 2012**

NOTICES

Disclaimers

Army Research Laboratory
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14. ABSTRACT
The Model Assessment Project conducted an evaluation of the wind forecasts produced by the U.S. Army Research Laboratory (ARL) Three Dimensional Wind Field (3DWF) model as initialized by the ARL Weather Running Estimate–Nowcast (WRE-N) model and the Air Force Weather Agency (AFWA) Weather Research and Forecasting (WRF) model. The WRE-N model is a 500 m resolution application of the Advanced Research version of the WRF (WRF-ARW) with its observation nudging four-dimensional data assimilation (FDDA) option. The AFWA WRF model is the operational version of the WRF-ARW, which is run in certain theaters at 1.67 km resolution. Both models were run over a domain centered near Los Angeles, CA. Wind profiles from the 3DWF model were extracted at each of five wind profiler sites located in the domain. Wind profile observations were collected from the profiler sites. The forecast and observed wind profile data was imported into spreadsheets for quality control inspection, plotting and the calculation of standard error statistics. Hourly statistics were aggregated into composite statistics for each profiler site and date for the five case study days. The statistical results are discussed with some tabular and graphical examples and conclusions are offered, which describe the results of the comparison.

15. SUBJECT TERMS
3DWF, WRF, WRE-N, AFWA, wind, forecast, score, error, statistics, profiler, case study

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1. Introduction

The U.S. Air Force (AF) was designated as the lead agency to respond to a Joint Urgent Operational Needs Statement (JUONS) addressing local meteorological sensing, hazard detection, and short-term forecasting in high resolution complex terrain domains. Based on the U.S. Army Research Laboratory (ARL) Battlefield Environment Division's current research, development, and tech transition relationship with the AF Director of Weather and Air Force Weather Agency (AFWA), ARL was identified as a primary research agency to meet the capability gaps addressed in the JUONS. One research area that ARL was involved in with AFWA to support this JUONS had to do with modifying and implementing the local fine-scale version of the Weather Running Estimate-Nowcast (WRE-N) and coupling it to the diagnostic Three-Dimensional Wind Field (3DWF) microscale wind model for use in complex terrain.

The ARL WRE-N has been designed as a storm-scale application of the Advanced Research version of the Weather Research and Forecast (WRF-ARW) model (Skamarock et al., 2008) and its observation nudging four-dimensional data assimilation (FDDA) option (Reen and Stauffer, 2010; Liu et al., 2005). Typically, the WRE-N is configured in a multi-nest configuration to produce a finest inner mesh of around 1 km grid spacing (i.e., 9 km/3 km/1 km) and to leverage an externally-generated global model for cold-start initial conditions and time-dependent lateral boundary conditions for the outermost nest. Typically, for ARL development and testing, this global model has been the National Center for Environmental Prediction's (NCEP) Global Forecast System (GFS) model (National Weather Service, 2003). The WRE-N is essentially a rapid-update cycling application of the WRF-ARW with FDDA and optimally can refresh itself at intervals up to hourly (dependent upon the observation network).

For the JUONS effort ARL wanted to provide a WRE-N capability that could work within the framework of the operational double-nest WRF-ARW configuration (5 km, 1.67 km), which AFWA has been running in certain theaters. The AFWA modeling configuration uses a 6-h-data assimilation cycling schedule with the intermittent WRF Three-Dimensional Variational (3DVAR) (Barker et al, 2003) software assimilating available observations onto the coarsest outer nest (5 km). The inner nest (1.67 km) solution is generated through interactive WRF-ARW nesting (i.e., no 3DVAR was applied directly to the 1.67 km nest). The ARL approach modified WRE-N by adopting a single-nest configuration of 500 m grid spacing, reducing the cycling or "refresh" frequency to every 6 h (consistent with AFWA), and using AFWA's 1.67 km fine nest forecasts for cold-start initial and time-dependent lateral boundary conditions (as opposed to GFS). For each WRE-N cycle a 6-h-forecast period was generated and evaluated (although AFWA actually ran their WRF-ARW cycles beyond 6 h).

2. Background

2.1 Model Design

The basic research experiment consisted of setting up both modeling systems (ARL's 500 m WRE-N and AFWA's WRF-ARW 5 km, 1.67 km) over a data-rich domain of southern California (near Los Angeles), so that comparisons using the 1800 Universal Time Coordinated (UTC) model cycle generated by both systems could be accomplished. These comparisons were made via the Three Dimensional Wind Field (3DWF) model wind profiles generated at a number of wind profiler sites in southern California, using both the WRE-N 500 m and AFWA 1.67 km fields for initial input. The hours from 1800 UTC to 0000 UTC were compared for each 6 h period. The idea was to see if the WRE-N approach at fine scales could offer promise in terms of improving 3DWF results for low-level boundary layer wind profiles. It should also be added that AFWA had to run cycles both at 1200 UTC and 1800 UTC, because the WRE-N required a 6 h pre-forecast FDDA period and, therefore, leveraged the 1200 UTC AFWA cycle for its own 1800 UTC cycle. Statistical metrics were computed to compare the 3DWF-AFWA WRF-ARW and 3DWF-ARL WRE-N wind profiles at the various wind profiler sites. A total of five case study days were selected in February and March of 2012 in order to provide a variant set of synoptic and mesoscale conditions. The days selected were February 7, February 9, February 16, March 1, and March 5. See figures 1−5.

The models were centered at latitude 34.5° N and longitude at 118.0° W. The 500 m nest WRE-N dimensions were 401 × 401 × 57, while the AFWA 1.67 km inner nest was 201 × 201 × 57, see figure 6. The observations used by the WRE-N FDDA are shown in figure 7 and figure 8 and consist of surface (including mesonet), radiosonde, cooperative agency boundary-layer wind profiler, and aircraft. The WRE-N and AFWA namelists for WRF-ARW were the same, except the WRE-N had model top of 50 hPa rather than 10 hPa, and WRE-N used a few slightly stronger numerical damping terms.

Several sub-domains were established for the 3DWF model, centered at various cooperative agency boundary-layer wind profiler sites identified in figure 7. The 3DWF was executed with a horizontal grid spacing of 50 m for each hour between 1800 UTC and 0000 UTC. At *each* hour a 3DWF simulation vertical wind profile was generated for *each* wind profiler location.

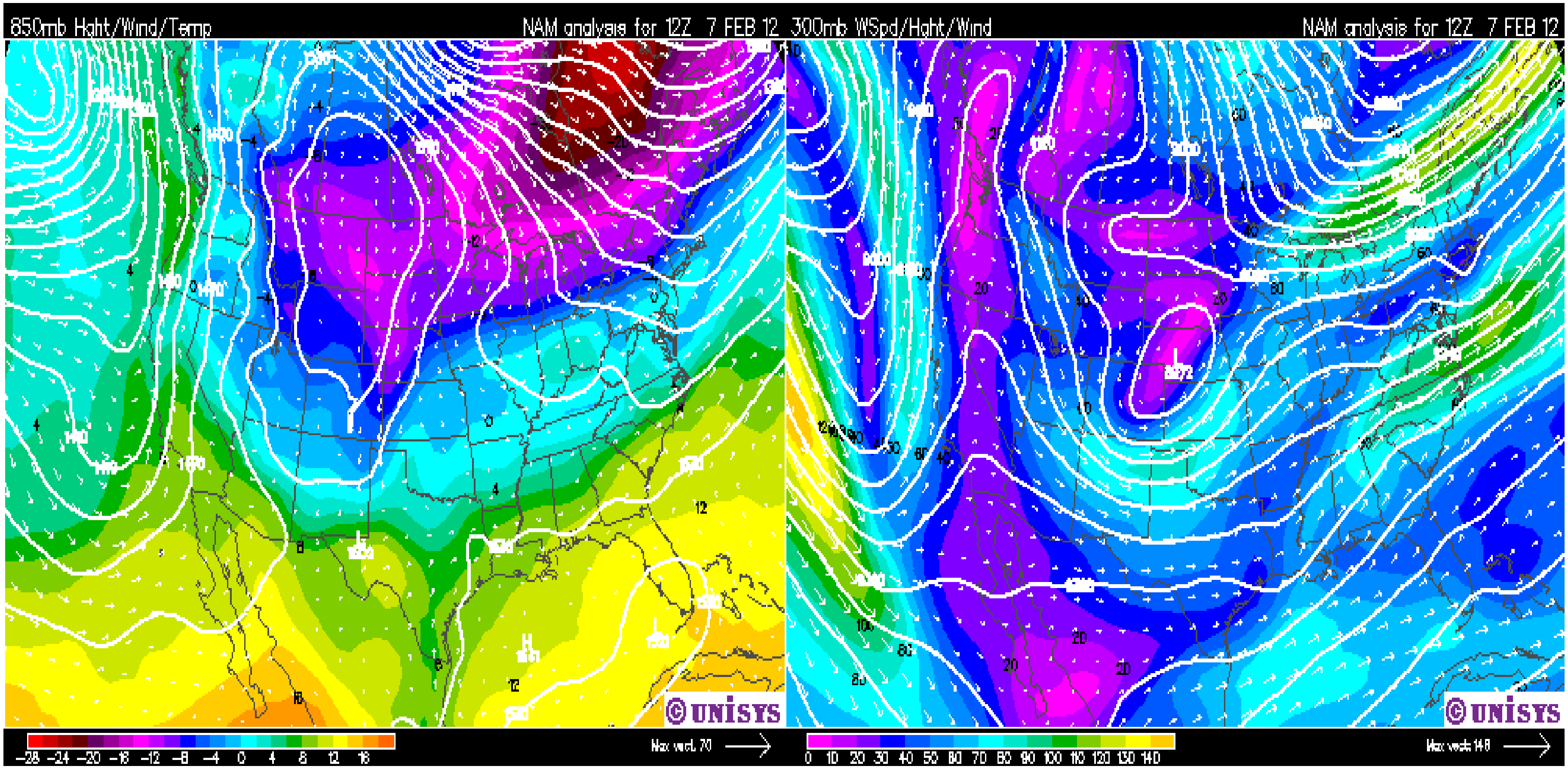

Figure 1. The 850 hPa and 300 hPa analysis charts for 1200 UTC, February 7, 2012.

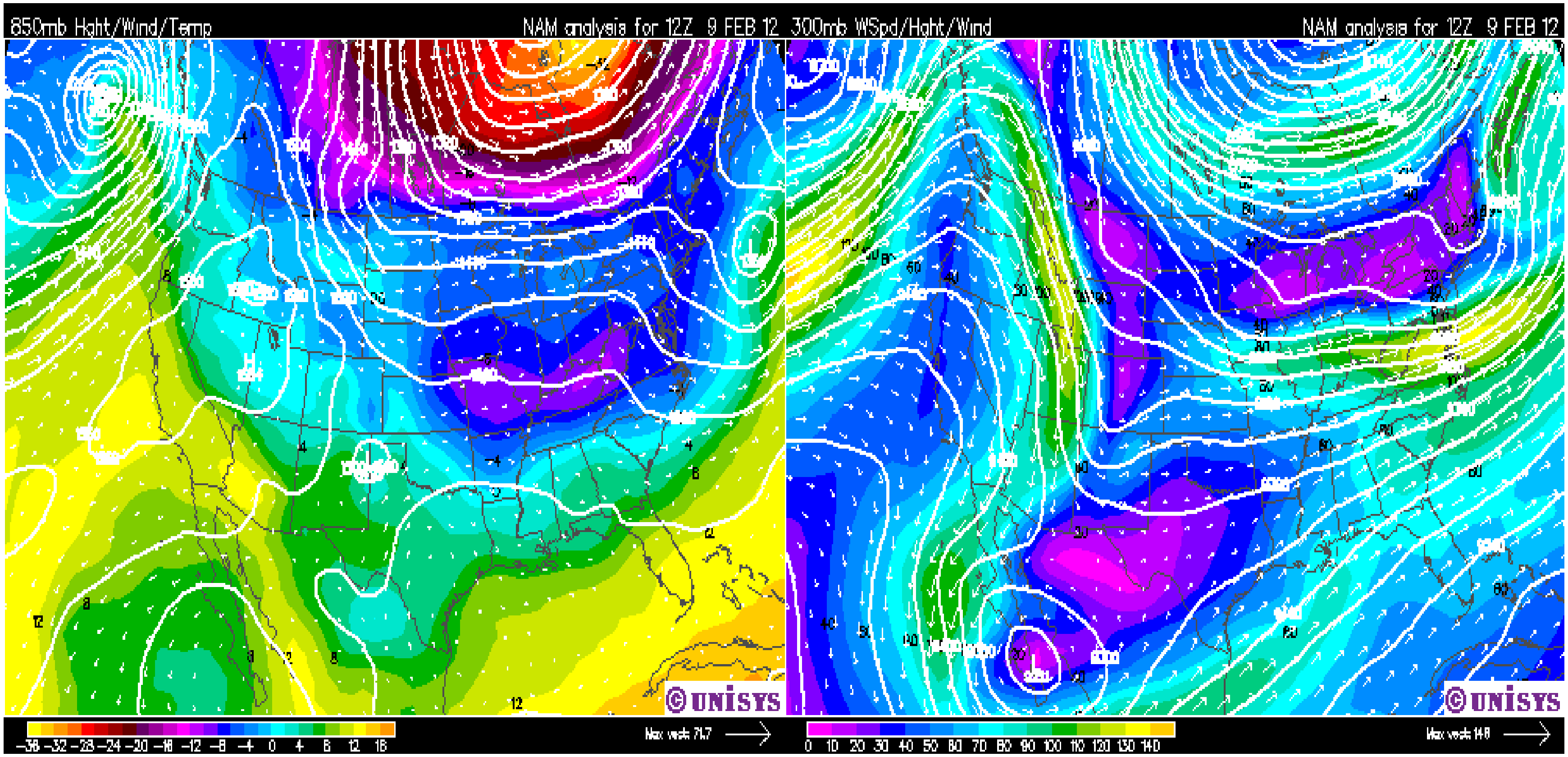

Figure 2. The 850 hPa and 300 hPa analysis charts for 1200 UTC, February 9, 2012.

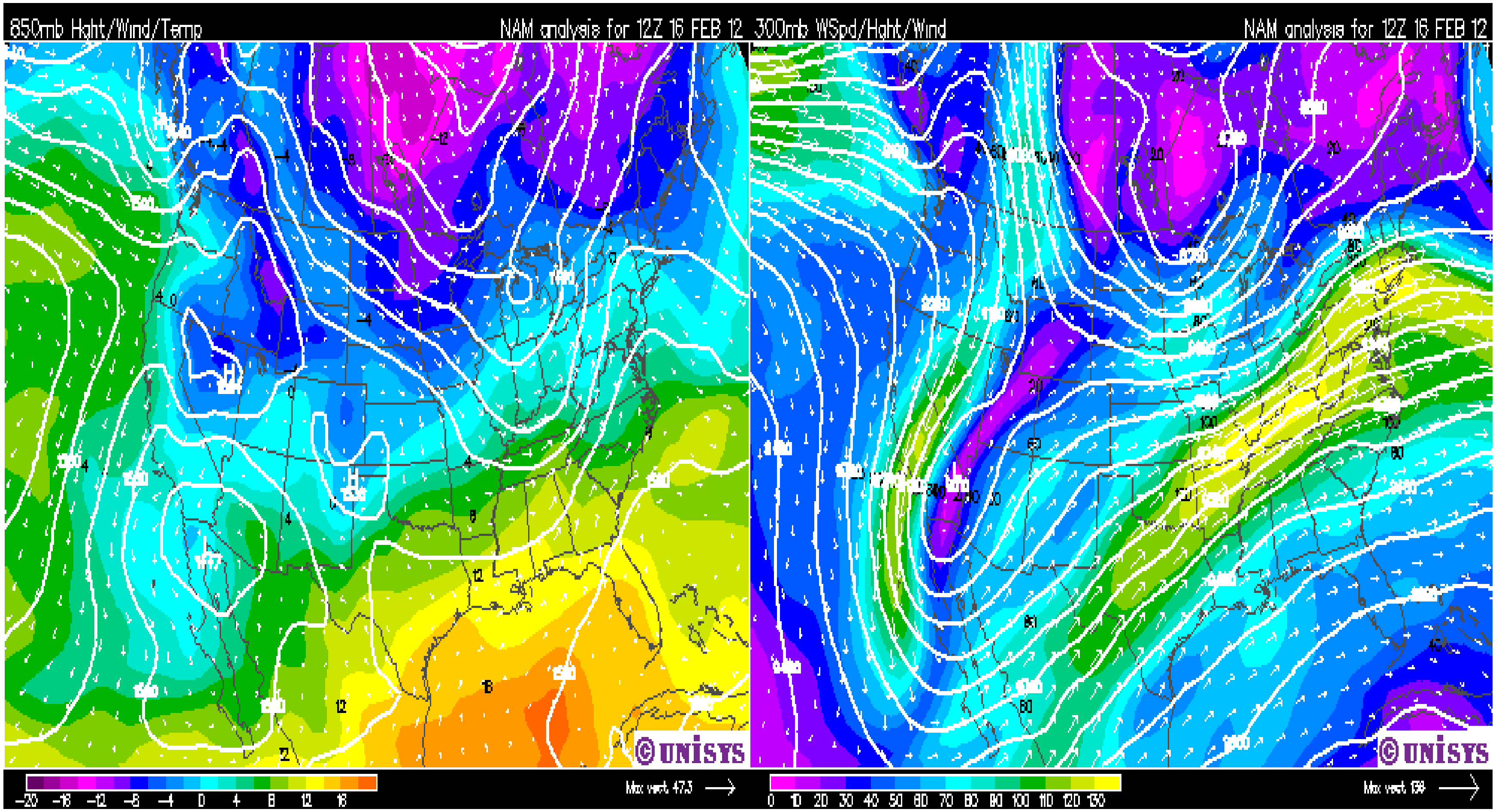

Figure 3. The 850 hPa and 300 hPa analysis charts for 1200 UTC, February 16, 2012.

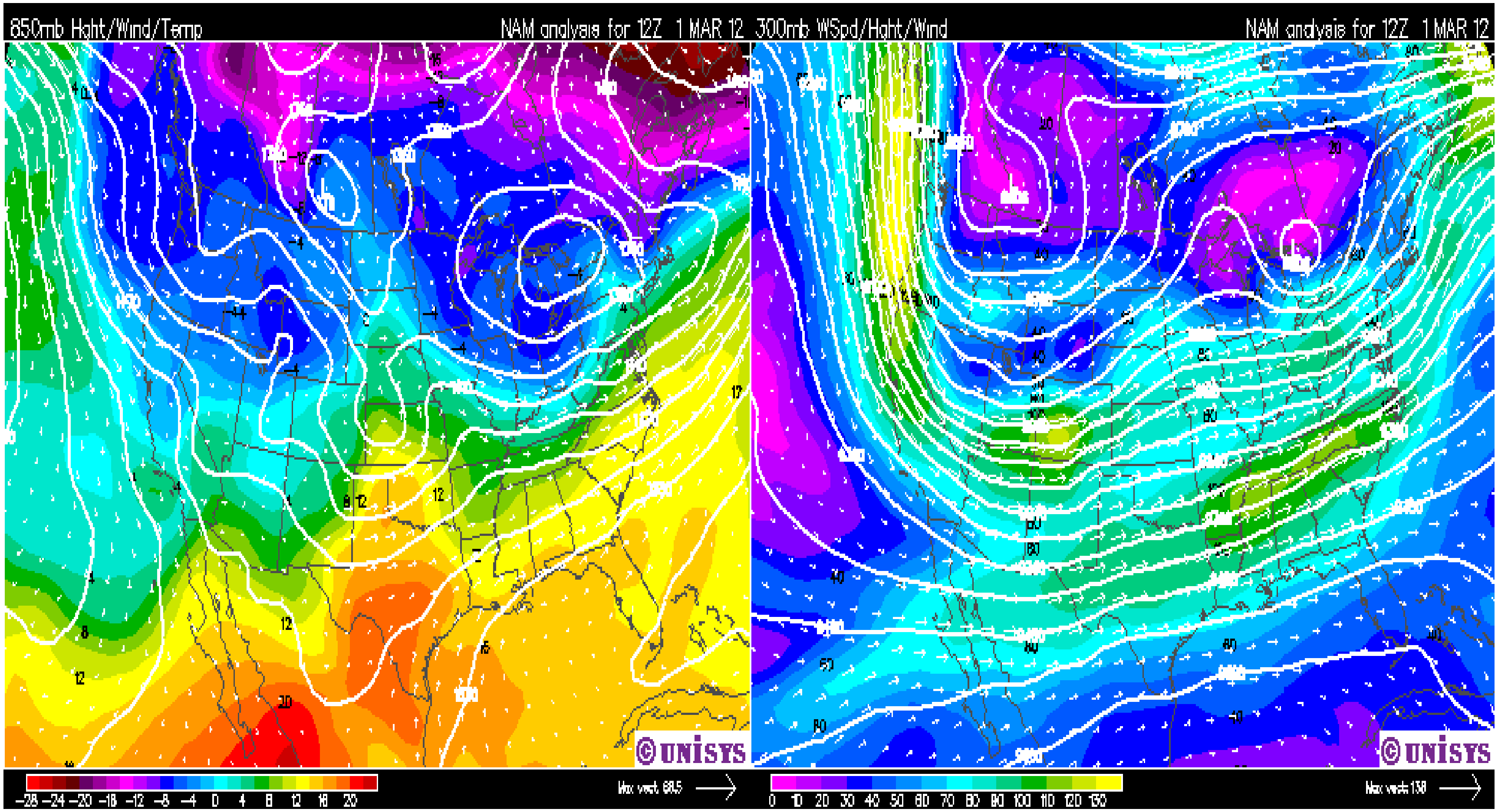

Figure 4. The 850 hPa and 300 hPa analysis charts for 1200 UTC, March 1, 2012.

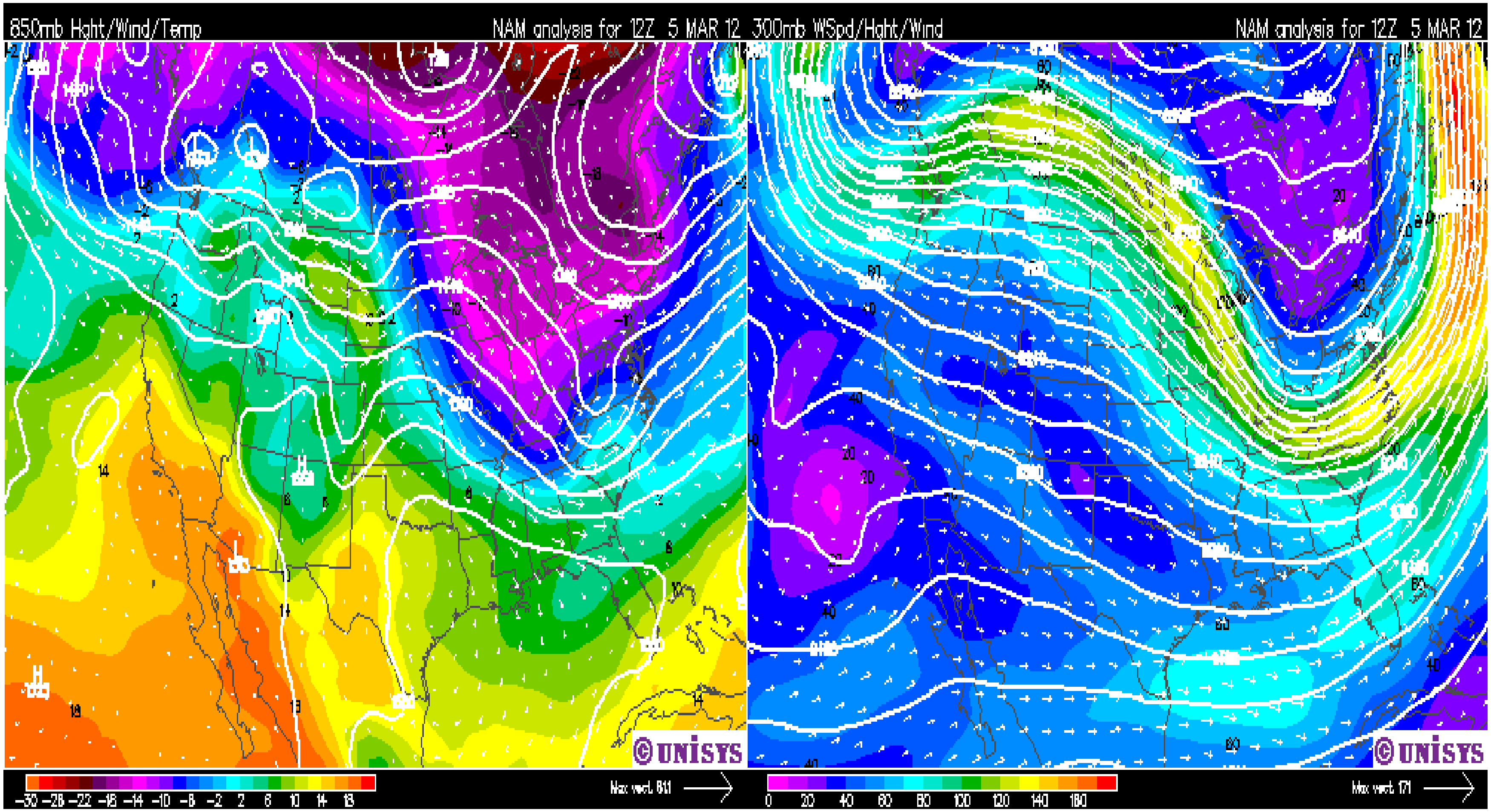

Figure 5. The 850 hPa and 300 hPa analysis charts for 1200 UTC, March 5, 2012.

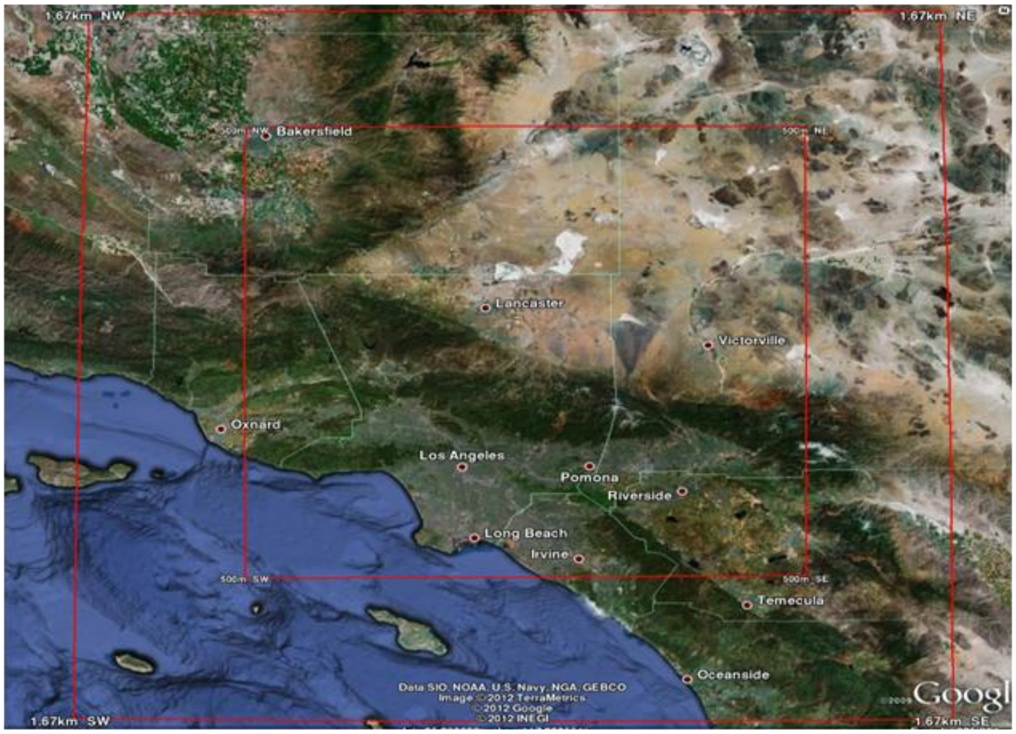

Figure 6. ARL 500 m nest inside AFWA 1.67 km nest centered just southeast of Lancaster, CA.

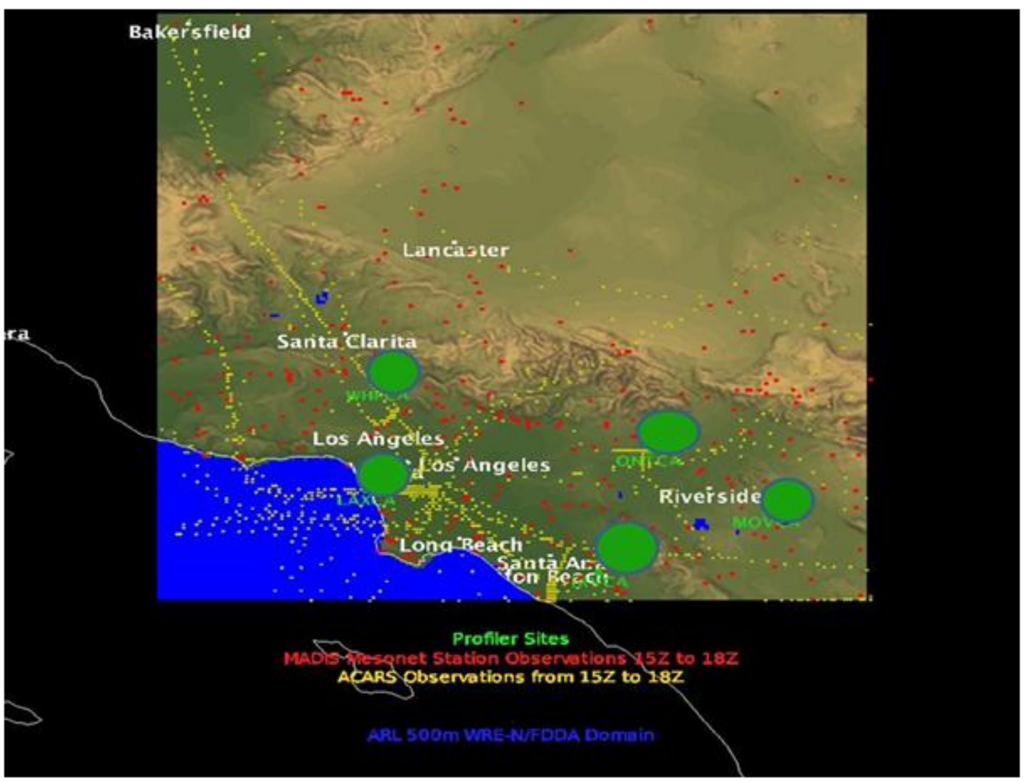

Figure 7. Example of observations and locations in 2-D used by WRE-N.

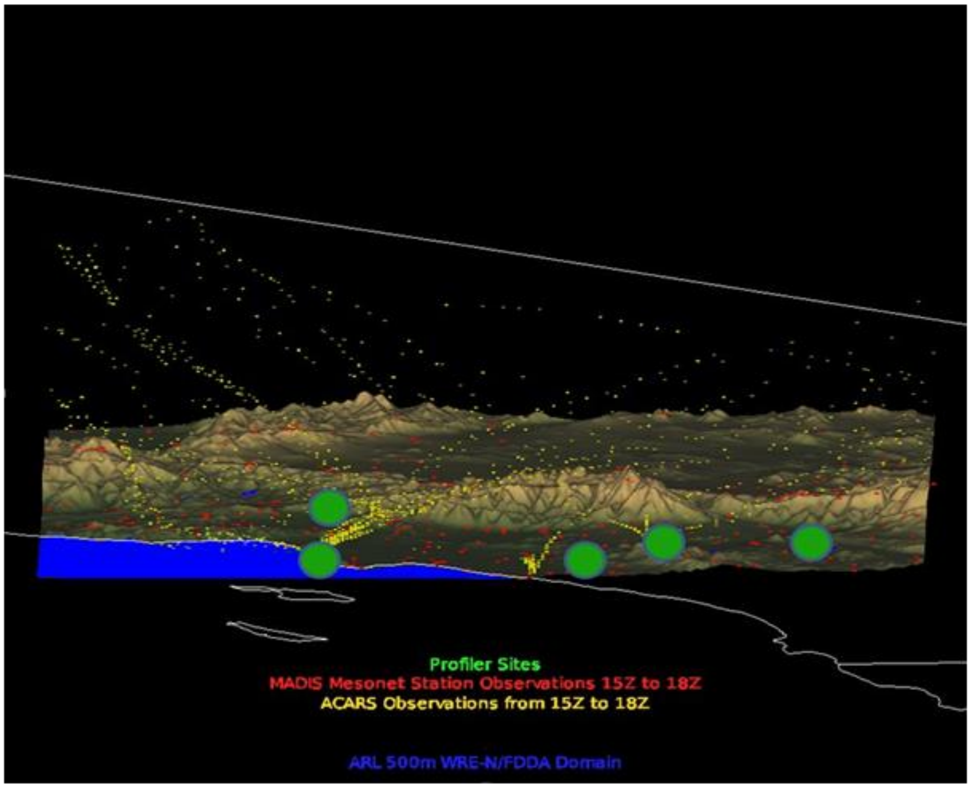

Figure 8. Example of observations and locations in 3-D used by WRE-N.

2.2 Assessment Data Collection and Processing

The output files for the 3DWF WRE-N and the 3DWF AFWA WRF model pairs and the observed profiler wind observations for the available sites for the five case study days were imported into Excel spreadsheets to produce plots comparing the model wind profiles with the observed profile. The model profile data was interpolated linearly to the profiler levels so that the model-observation differences could be computed at the same level. This produced the raw error statistics from which the Mean Error (ME), the Mean Absolute Error (MAE), the Mean Squared Error (MSE), and the Root Mean Squared Error (RMSE) were calculated over the entire profile for each hour from a given site and date. Composite values for ME, MAE, MSE, and RMSE were generated from these data by aggregating the error data for all hours from a given site and date and then re-computing over the larger set of raw errors. The numbers of samples for the composite values were considered large enough to enable the computation of 95% normal confidence intervals, which were applied to the value to determine when the model differences were statistically significant.

The results section contains some examples of the plots and tabular data, which characterize the three possible situations encountered for these case studies. Figures 9 and 10 and table 1 depict the wind speed, direction plots, and error statistics for a situation where the 3DWF WRE-N scored better than the 3DWF AFWA WRF. Figures 11and 12 and table 2 depict the wind speed, direction plots, and error statistics for a situation where the 3DWF AFWA WRF scored better

than the 3DWF WRE-N. Figures 13 and 14 and table 3 depict the wind speed, direction plots, and error statistics for a situation where the 3DWF AFWA WRF and the 3DWF WRE-N scored about the same.

3. Results

3.1 Examples from Model Performance Case Studies

3.1.1 WRE-N-3DWF Outperforms AFWA WRF 3DWF

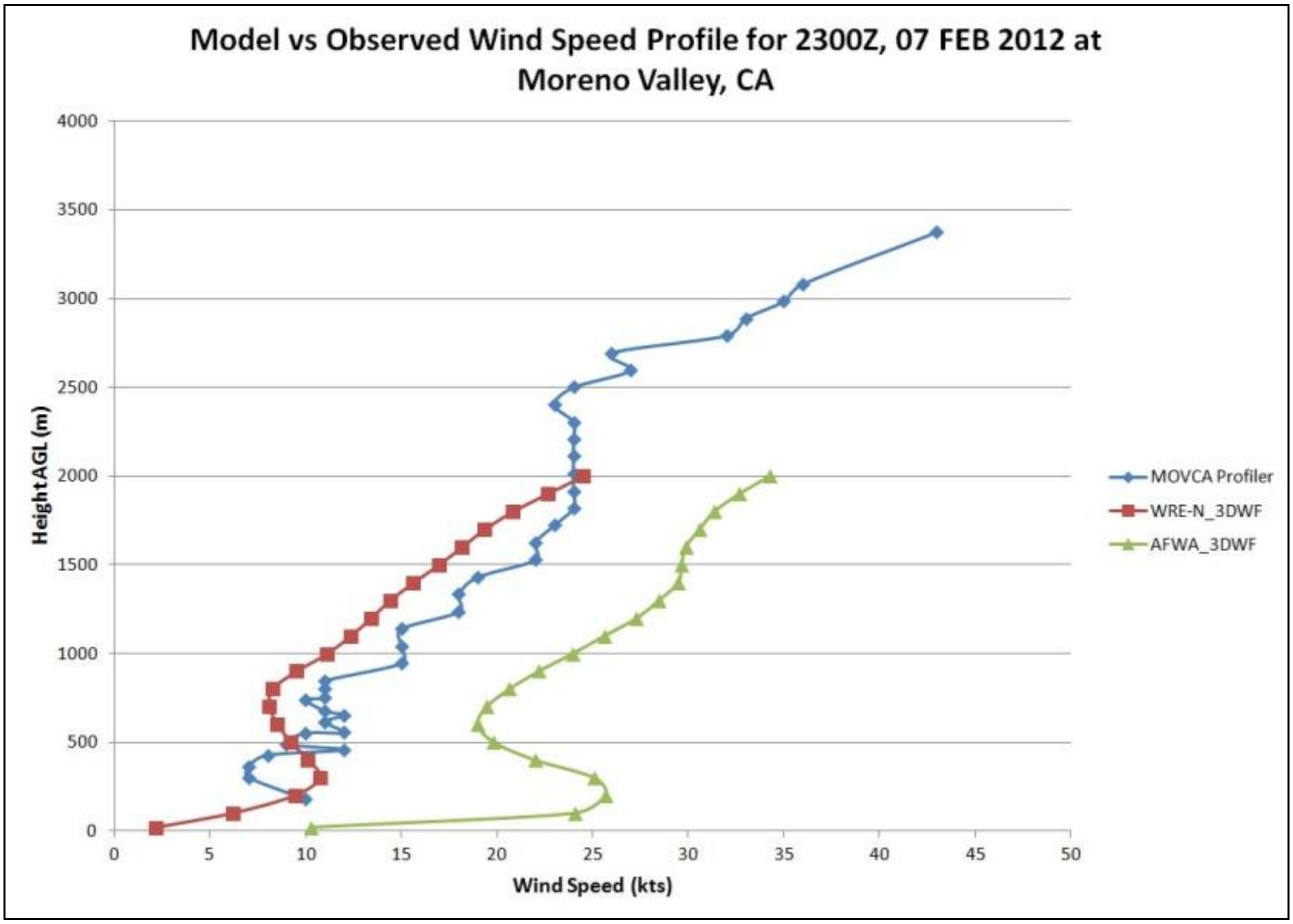

Figure 9. Model and observed wind speed profiles, 2300Z, February 7, 2012, Moreno Valley, CA.

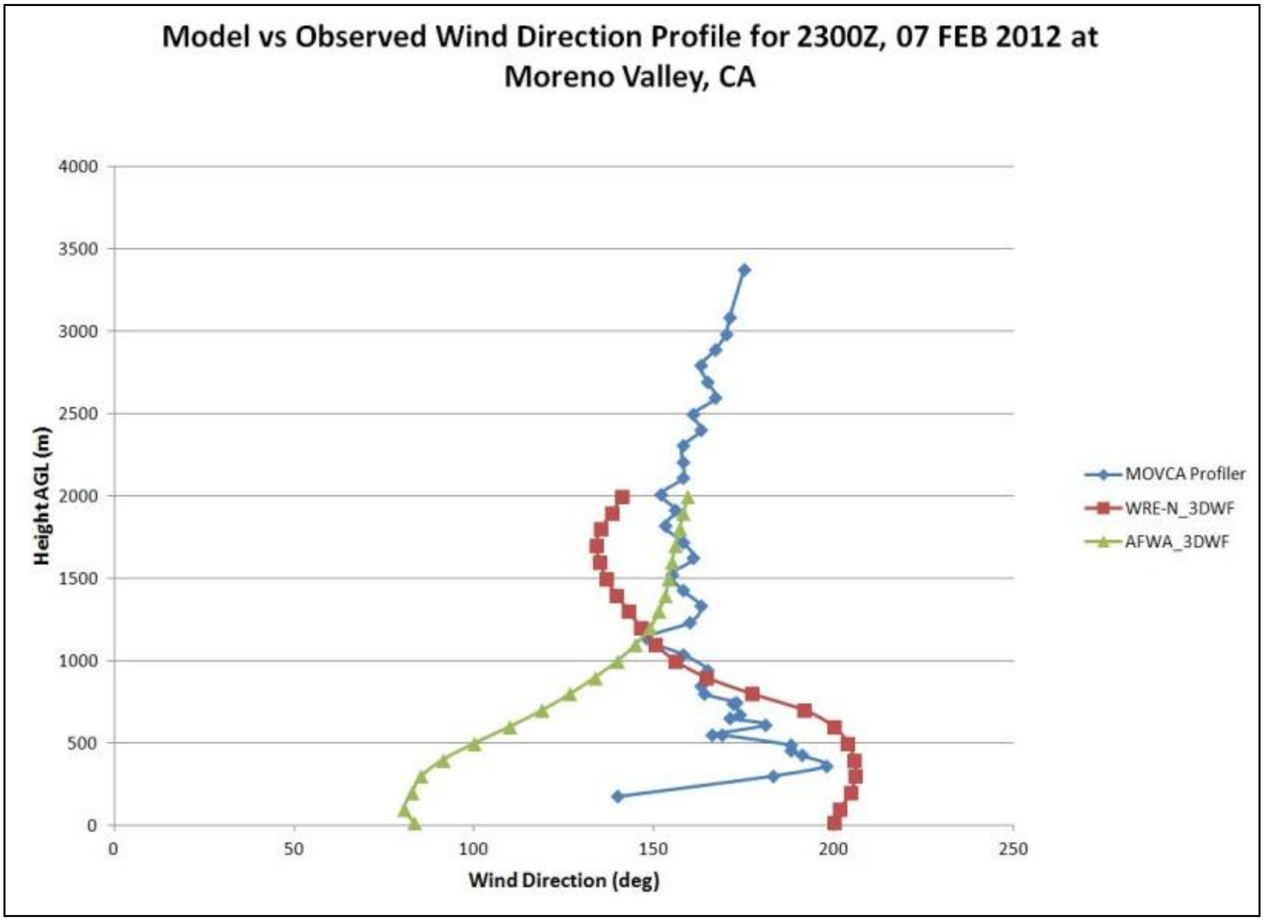

Figure 10. Model and observed wind direction profiles, 2300Z, February 7, 2012, Moreno Valley, CA.

3.1.2 AFWA WRF 3DWF Outperforms WRE-N 3DWF

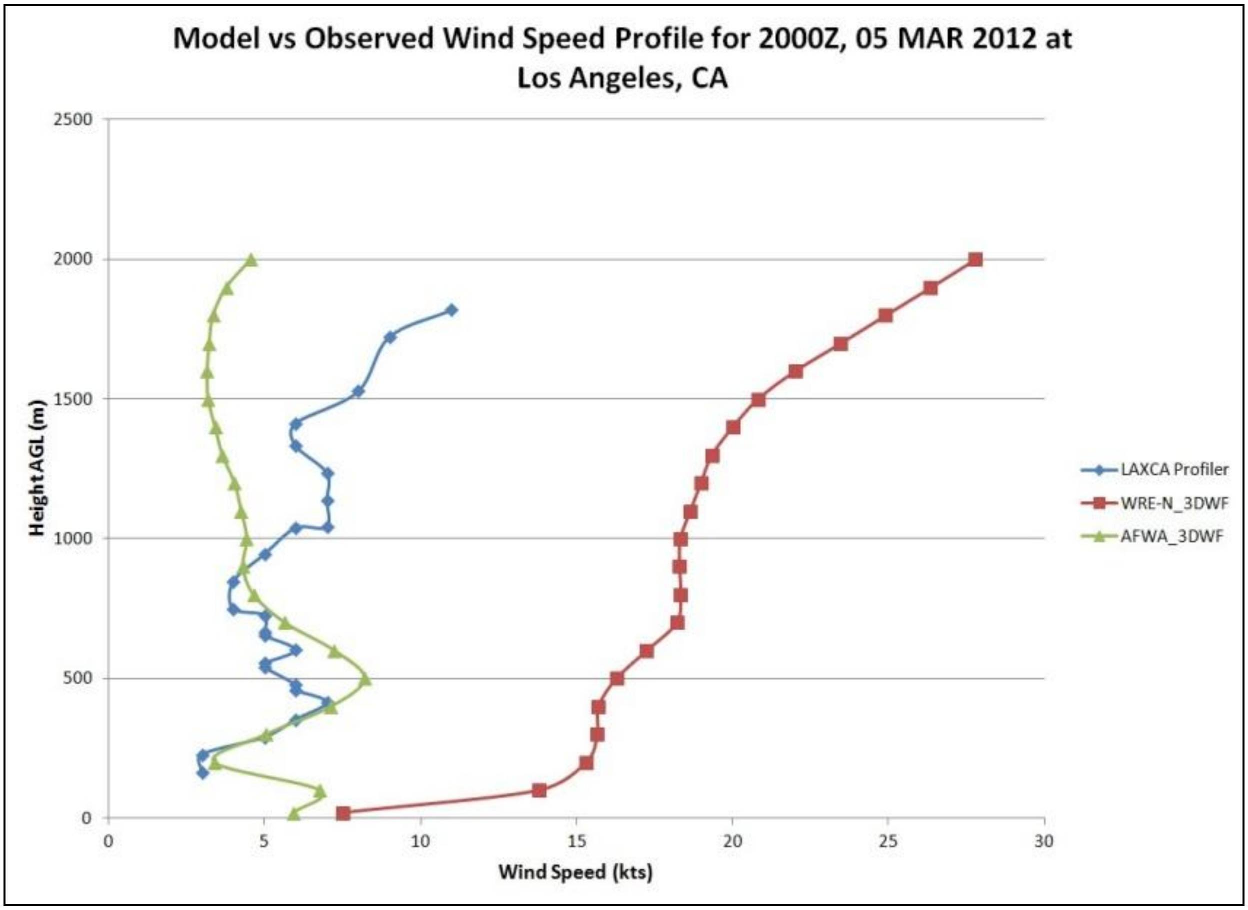

Figure 11. Model and observed wind speed profiles, 2000Z, March 5, 2012, Los Angeles, CA.

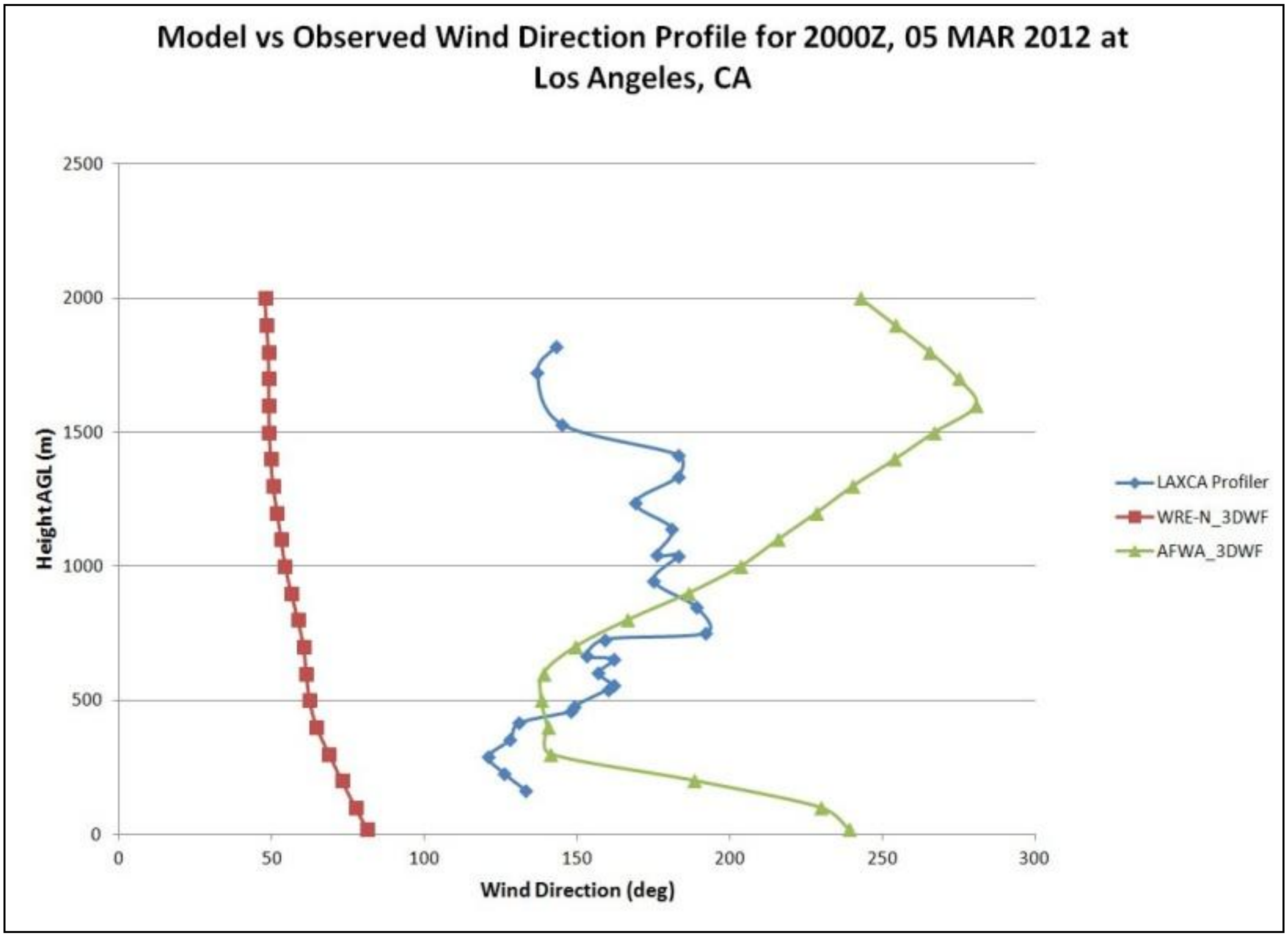

Figure 12. Model and observed wind direction profiles, 2000Z, March 5, 2012, Los Angeles, CA.

3.1.3 WRE-N 3DWF and AFWA WRF 3DWF Perform About the Same

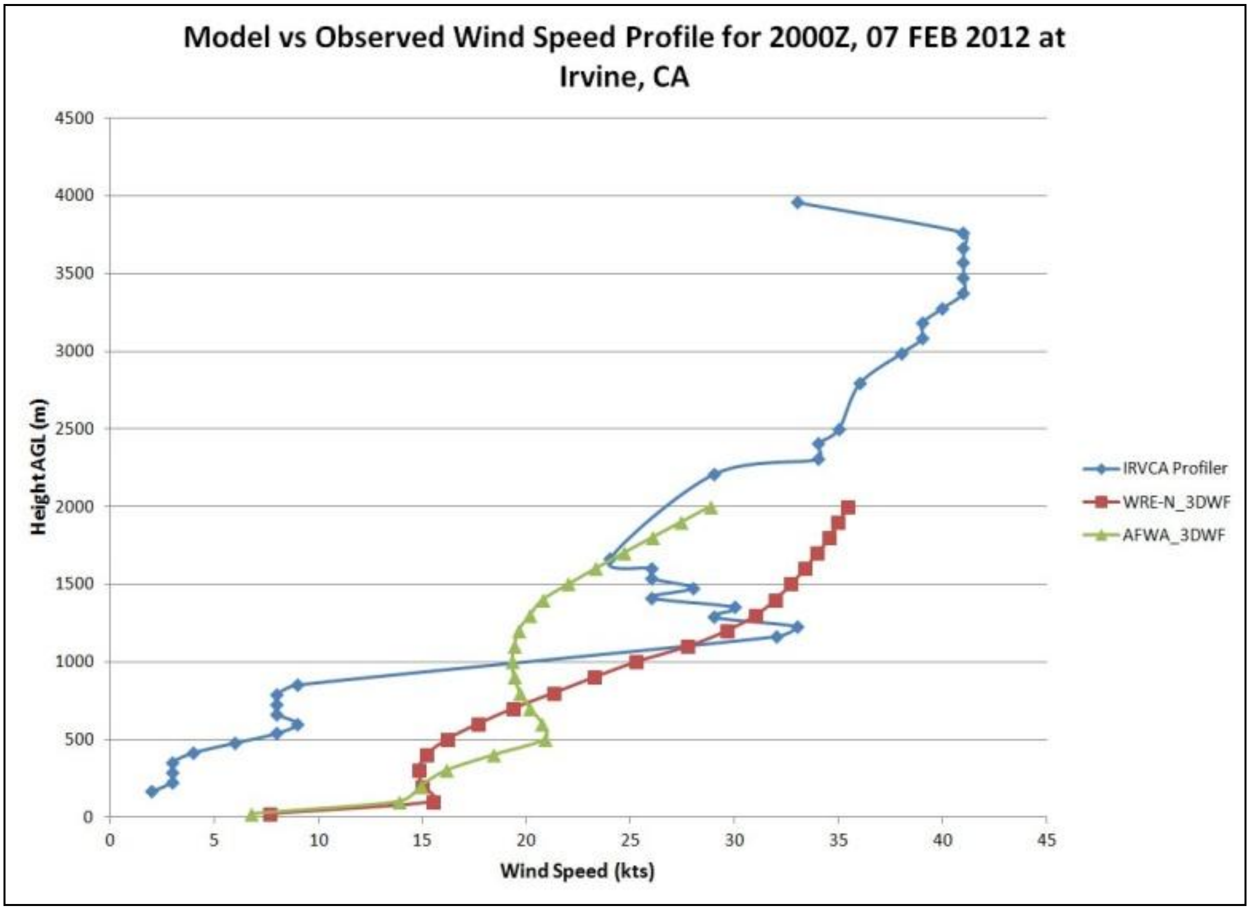

Figure 13. Model and observed wind speed profiles, 2000Z, February 7, 2012, Irvine, CA.

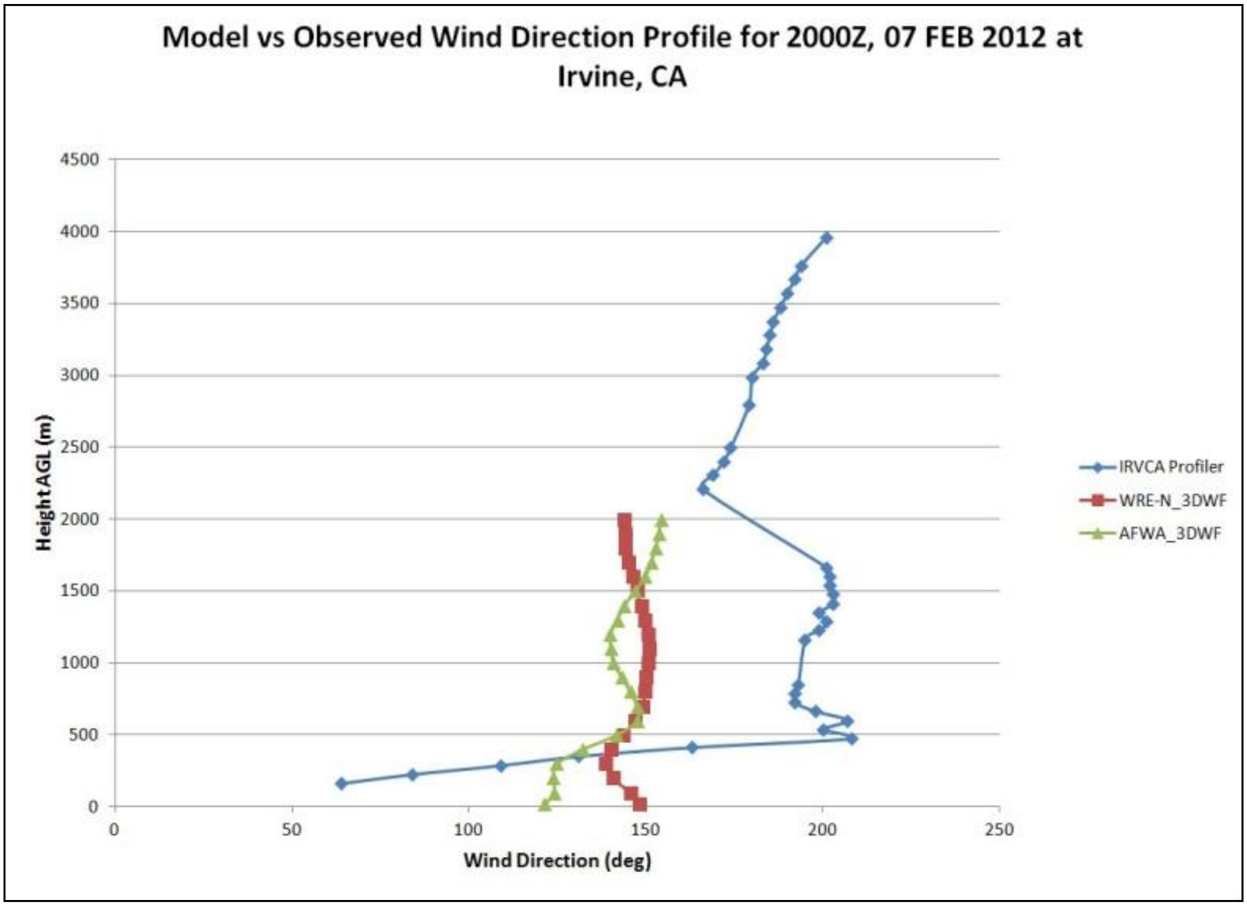

Figure 14. Model and observed wind direction profiles, 2000Z, February 7, 2012, Irvine, CA.

3.2 Composite Error Statistics for Case Study Examples

Table 1. 3DWF error statistics for Moreno Valley, CA for February 7, 2012, 2300Z.

WRE-N ME—Spd (kts)	**AFWA ME—Spd**	**WRE-N MAE—Spd**	**AFWA MAE—Spd**	**WRE-N RMSE—Spd**	**AFWA RMSE—Spd**
−2.07	10.06	2.78	10.06	2.98	10.42
WRE-N ME—Dir (°)	**AFWA ME—Dir**	**WRE-N MAE—Dir**	**AFWA MAE—Dir**	**WRE-N RMSE—Dir**	**AFWA RMSE—Dir**
5.83	−42.04	18.73	42.56	22.32	54.90

Table 2. 3DWF error statistics for Los Angeles, CA for March 5, 2012, 2000Z.

WRE-N ME—Spd (kts)	**AFWA ME—Spd**	**WRE-N MAE—Spd**	**AFWA MAE—Spd**	**WRE-N RMSE—Spd**	**AFWA RMSE—Spd**
12.26	−0.70	12.26	2.06	12.36	2.72
WRE-N ME—Dir (°)	**AFWA ME—Dir**	**WRE-N MAE—Dir**	**AFWA MAE—Dir**	**WRE-N RMSE—Dir**	**AFWA RMSE—Dir**
−99.05	28.15	99.05	40.99	102.32	55.70

Table 3. 3DWF error statistics for Irvine, CA for February 7, 2012, 2000Z.

WRE-N ME—Spd (kts)	AFWA ME—Spd	WRE-N MAE—Spd	AFWA MAE—Spd	WRE-N RMSE—Spd	AFWA RMSE—Spd
8.04	4.34	8.62	10.20	9.42	10.99
WRE-N ME—Dir (°)	**AFWA ME—Dir**	**WRE-N MAE—Dir**	**AFWA MAE—Dir**	**WRE-N RMSE—Dir**	**AFWA RMSE—Dir**
−32.20	−37.60	48.71	48.61	50.81	50.96

3.3 Analysis of Statistical Comparisons

Note: For purposes of the discussion in this section, when WRE-N and WRF acronyms are used here, they refer to the 3DWF output initialized by both models]

All composite error statistics for each model were compared to determine which model scored best statistically. Only the cases where the difference in scores was clearly statistically significant were included in this analysis. The analysis treats a case as a comparison of the same error statistic, and the total number of cases considers the comparisons for all three error statistics namely ME, MAE, and RMSE lumped together. Table A-1 in the appendix shows the composite statistics with the cases where significant differences were determined are highlighted. The following summarizes the outcomes of the score comparisons, and caution should be used in inferring conclusions about model performance from these few early case studies.

The maximum possible cases were 79. Out of the 79 cases there were 49 for which the WRE-N outscored the AFWA WRF. The AFWA WRF outscored the WRE-N for the other 30 cases.

The case study data for all profiler sites and dates were divided into two groups to separate out the cases during which the mean wind speed was less than 10 knots and during which the mean wind speed exceeded 10 knots. The above method for determining the model performance score were then applied to each group.

There were a total of 56 cases with significant differences for speed less than 10 knots. For 31 of these cases, the WRE-N outscored the AFWA WRF. For 25 of these cases, the AFWA WRF outscored the WRE-N.

There were a total of 23 cases with significant differences for speed greater than 10 knots. For 18 of these cases, the WRE-N outscored the AFWA WRF. For five of these cases, the AFWA WRF outscored the WRE-N.

The above results were broken down to separate the results considering speed error statistic comparisons and direction error statistic comparisons. The same analysis as above was performed for less than and greater than 10 knots mean wind speed.

For speed, the total number of cases where there were significant differences for which the mean wind speed was less than 10 knots was 31. In 18 of those cases, the WRE-N outscored the AFWA WRF. For 13 of those cases, the AFWA WRF outscored the WRE-N.

For speed, the total number of cases where there were significant differences for which the mean wind speed was greater than 10 knots was 16. In 13 of those cases, the WRE-N outscored the AFWA WRF. For three of those cases, the AFWA WRF outscored the WRE-N.

For direction, the total number of cases where there were significant differences for which the mean wind speed was less than 10 knots was 25. In 13 of those cases, the WRE-N outscored the AFWA WRF. For 12 of those cases, the AFWA WRF outscored the WRE-N.

For direction, the total number of cases where there were significant differences for which the mean wind speed was greater than 10 knots was 7. In five of those cases, the WRE-N outscored the AFWA WRF. For two of those cases, the AFWA WRF outscored the WRE-N.

These results suggest that the WRE-N may have the advantage in situations where the atmospheric flow is stronger and less of an advantage when the flow is weak.

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Appendix

Table A-1 contains the composite error statistics for each model, profiler site, and case study date. The statistics are aggregated over all hours for which forecasts were made.

Table A-1. Composite error statistics by site for each date aggregated over all hours. Highlighted entries mark significant differences.

Date	Statistic	MOVCA	IRVCA	LAXCA	ONTCA	WHPCA
		WREN/AFWA	WREN/AFWA	WREN/AFWA	WREN/AFWA	WREN/AFWA
7 FEB	SPD ME	−6.50/3.23	8.95/6.20	7.82/7.33	2.84/3.98	N/A
	SPD MAE	7.25/12.44	9.33/8.24	8.06/8.01	4.73/6.75	N/A
	SPD RMSE	10.66/13.94	10.68/9.94	9.72/10.15	6.00/8.82	N/A
	DIR ME	−8.49/−30.35	−12.28/−13.00	−9.13/−2.13	−13.92/−13.44	N/A
	DIR MAE	21.48/36.05	24.44/24.35	12.25/18.24	32.50/40.37	N/A
	DIR RMSE	30.20/45.01	29.98/29.92	15.49/23.37	49.59/66.37	N/A
9 FEB	SPD ME	−1.97/0.69	2.02/1.54	0.79/−0.54	0.34/1.04	−0.19/−0.23
	SPD MAE	3.04/4.49	2.62/2.75	2.10/1.98	2.50/2.27	1.76/2.20
	SPD RMSE	3.66/5.30	3.46/3.39	2.61/2.50	3.03/2.89	2.20/2.71
	DIR ME	−8.61/7.57	−2.20/−4.25	−2.53/−16.25	15.60/41.92	12.24/9.67
	DIR MAE	23.67/30.94	20.95/32.97	19.70/29.11	36.51/56.27	40.51/39.02
	DIR RMSE	33.04/46.45	31.95/41.85	33.74/44.87	56.08/68.25	55.22/52.19
16 FEB	SPD ME	7.96/13.71	7.71/19.49	7.17/0.25	−4.56/19.02	6.05/13.08
	SPD MAE	8.75/14.34	12.20/20.18	7.94/5.83	9.53/20.04	6.80/15.50
	SPD RMSE	10.31/17.29	15.69/25.11	10.11/7.87	11.42/22.79	9.81/20.14
	DIR ME	−16.28/−17.66	−54.73/−48.05	−2.41/4.54	−21.64/−18.27	−4.65/−9.53
	DIR MAE	31.38/31.16	56.08/49.73	31.06/29.32	22.13/19.82	22.00/18.82
	DIR RMSE	39.79/41.62	74.14/68.45	42.25/43.52	25.79/21.84	38.96/37.44
1 MAR	SPD ME	3.42/3.34	4.31/5.74	3.45/2.64	−0.18/6.04	22.78/3.79
	SPD MAE	3.95/5.03	4.80/6.54	4.01/3.08	2.20/6.05	22.78/4.33
	SPD RMSE	4.91/6.37	5.49/8.28	5.45/3.64	2.89/6.92	23.61/6.65
	DIR ME	18.73/39.83	67.20/67.71	−2.64/27.31	21.61/22.55	16.03/63.01
	DIR MAE	26.82/45.16	69.25/76.29	25.15/39.78	29.20/28.24	41.72/71.04
	DIR RMSE	37.99/55.43	84.31/87.53	37.45/56.21	38.24/36.02	51.71/87.71
5 MAR	SPD ME	−0.19/−0.56	0.07/0.65	3.82/0.34	−1.09/0.02	−1.10/−2.62
	SPD MAE	2.43/2.21	2.75/1.76	5.01/2.11	2.52/2.68	1.66/2.72
	SPD RMSE	3.11/2.88	3.54/2.22	6.96/2.67	2.98/3.43	2.09/3.23
	DIR ME	−32.50/4.32	15.47/43.00	−34.97/32.17	−38.17/7.84	52.56/35.32
	DIR MAE	51.21/36.16	78.59/68.86	45.59/43.28	43.63/23.64	52.56/35.98
	DIR RMSE	66.78/48.53	91.39/78.59	60.64/53.27	51.66/36.52	56.14/44.56

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List of Symbols, Abbreviations, and Acronyms

3DVAR	Three-Dimensional Variational
3DWF	Three Dimensional Wind Field
ACARS	Aircraft Communications Addressing and Reporting and System
AF	Air Force
AFWA	Air Force Weather Agency
AGL	Above Ground Level
ARL	U.S. Army Research Laboratory
ARW	Advanced Research WRF
FDDA	Four Dimensional Data Assimilation
GFS	Global Forecast System
IRVCA	Irvine, CA Profiler Site
JUONS	Joint Urgent Operational Needs Statement
LAXCA	Los Angeles, CA Profiler Site
MADIS	Meteorological Assimilation Data Ingest System
MAE	Mean Absolute Error
ME	Mean Error
MOVCA	Moreno Valley, CA Profiler Site
MSE	Mean Squared Error
ONTCA	Ontario, CA Profiler Site
RMSE	Root Mean Square Error
SEMS	Systems Engineering, Management and Sustainment
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
UTC	Universal Time Coordinated
WHPCA	Whiteman Airport, CA Profiler Site
WRE-N	Weather Running Estimate - Nowcast
WRF	Weather Research and Forecasting

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